INVESTIGATION OF THREE-DIMENSIONAL EFFECTS ON FLAME STABILIZATION IN A SUBSONIC FLOW WITH PREMIXED COMBUSTION*

R. A. Balabanov[1,2]

[1]Moscow Institute of Physics and Technology (MIPT), 9 Institutsky Lane, Dologoprudny 141701, Moscow Region, Russian Federation
[2]Central Aerohydrodynamic Institute named after Prof. N. E. Zhukovky (TsAGI), 1 Zhukovsky Str., Zhukovsky 140180, Moscow Region, Russian Federation

Abstract: The results of three-dimensional calculations of P. Magre *et al.* experiment (ONERA) with premixed methane–air combustion in a model channel with backward step are presented. The calculations are carried out with EPaSR (Extended Partially Stirred Reactor) model to take into account the first channel of turbulence–chemistry interaction. The problems caused by transition to non-Boussinesq models of DRSM class are discussed in the article. The article offers a solution to the problem caused by the absence of turbulent kinetic energy production in the flame front which arises in calculations with DRSM models. The significant influence of non-Boussinesq models on the flow structure is demonstrated. The influence of the transversal inhomogeneity of the velocity field on the flame flashback formation region is highlighted. The application of the two-way turbulence–chemistry interaction model EPaSR-PrOm shows that the side walls heat exchange severely influences the field of turbulent Prandtl number decreasing its value compared to that of the two-dimensional calculation.

Keywords: DRSM; flame flashback; turbulence–chemistry interaction

DOI: 10.30826/CE24170402 **EDN:** NSMKDK

Figure Captions

Figure 1 The mesh for the computation domain

Figure 2 Comparison of turbulent kinetic energy fields in two-dimensional simulations of ONERA experiment: (*a*) EPaSR model with SSG-LRR-ω; and (*b*) EPaSR model with BSL k–ω

Figure 3 Improved instantaneous field of turbulent kinetic energy in the three-dimensional simulation of ONERA experiment with EPaSR and SSG-LRR-ω with pressure dilatation term correction

Figure 4 Comparison of instantaneous temperature isosurfaces colored by vertical velocity: (*a*) EpaSR with Baseline k–ω and the PrOm model; and (*b*) EpaSR with SSG-LRR-ω taking into account dilatation correction

Figure 5 Comparison of temperature profiles in two-dimensional (solid curves) and three-dimensional (dashed curves) calculations with the EPaSR Baseline k–ω (upper row), EPaSR PrOm Baseline k–ω (lower row, black curves), and EPaSR SSG-LRR-ω models (lower row, grey curves) with experiment (signs): (*a*) $x = 0.1$ m; (*b*) 0.25; and (*c*) $x = 0.34$ m

Figure 6 Comparison of transversal velocity and streamlines in calculation with EPaSR Baseline k–ω (*a*) and EPaSR SSG-LRR-ω (*b*) models

Figure 7 Connection between transversal vortices and transversal inhomogeneity of the flame front caused by regions of flame flashback in calculation with EPaSR SSG-LRR-ω

Figure 8 The field of turbulent Prandtl number in two-dimensional (*a*) and in three-dimensional (*b*) calculations

Acknowledgments

The research described in sections 3 and 4 was supported by the grant of the Ministry of Science and High Education of the Russian Federation (contract No. 14.G39.31.0001 dated 13.02.2017). The author is grateful to V. A. Sabelnikov for the discussion on the effect of pressure dilatation term on turbulence models and useful recommendations as well as to his scientific adviser V. V. Vlasenko for discussion and assistance with editing the manuscript.

*The paper is based on the work that was presented at the 11th International Symposium on Nonequilibrium Processes, Plasma, Combustion, and Atmospheric Phenomena (NEPCAP), October 7–11, 2024, Sochi, Russia.

References

1. Magre, P., P. Moreau, G. Collin, R. Borghi, and M. Péalat. 1987. Further studies by CARS of premixed turbulent combustion in a high velocity flow. *Combust. Flame* 71(2):147–168. doi: 10.1016/0010-2180(88)90004-1.
2. Balabanov, R. A., V. V. Vlasenko, and A. Yu. Nozdrachev. 2024. Opisanie predvaritel'no peremeshannogo turbulentnogo goreniya v kanale so stupen'koy pri pomoshchi modeley klassa PaSR [Description of premixed turbulent combustion in a channel with a step using partially stirred reactor models]. *Combust. Explo. Shock Waves* 60(4):44–55. doi: 10.15372/FGV2024.9453.
3. Lewis, B., and G. von Elbe. 1987. *Combustion, flames and explosions of gases*. 3rd ed. Orlando, FL: Academic Press. 740 p.
4. Matyushenko, A. A., and A. V. Garbaruk. 2017. Nonlinear correction for the k–ω SST turbulence model. *J. Phys. Conf. Ser.* 929:012102. doi: 10.1088/1742-6596/929/1/012102.
5. Cecora, R.-D., R. Radespiel, B. Eisfeld, and A. Probst. 2015. Differential Reynolds stress modeling for aeronautics. *AIAA J.* 53(3):739–755. doi: 10.2514/1.J053250.
6. Pettersson Reif, B., and H. Andersson. 2002. Prediction of turbulence-generated secondary mean flow in a square duct. *Flow Turbul. Combust.* 68:41–61. doi: 10.1023/A:1015611721026.
7. Oh, M. T. 1995. Assessment of Reynolds stress turbulence closures for separated flow over backward-facing step. *Transactions Korean Society Mechanical Engineers* 19(11):3014–3021. doi: 10.22634/KSME.1995.19.11.3014.
8. Gibson, M. M., and B. E. Launder. 1978. Ground effects on pressure fluctuations in the atmospheric boundary layer. *J. Fluid Mech.* 86(3):491–511. doi: 10.1017/S0022112078001251.
9. Petrova, N. 2015. Turbulence chemistry interaction models for numerical simulation of aeronautical propulsion systems. Palaiseau: Ecole polytechnique. PhD Diss. 316 p.
10. Shiryaeva, A. A. 2018. Modelirovanie vysokoskorostnykh techeniy so smeshannymi rezhimami turbulentnogo goreniya na osnove trekhmernykh uravneniy Reynol'dsa [Modeling of high speed flows with premixed regimes of turbulent combustion on the basis of three-dimensional Reynolds equations]. Zhukovsky. PhD Diss. 217 p.
11. Fureby, C. 2007. Comparison of flamelet and finite rate chemistry LES for premixed turbulent combustion. AIAA Paper No. 1413-2007.
12. Balabanov, R. A., V. V. Vlasenko, and A. A. Shiryaeva. 2022. Opyt validatsii modeley turbulentnogo goreniya klassa PaSR i plany razvitiya etikh modeley primenitel'no k kameram sgoraniya gazoturbinnykh ustanovok [Experience in validation of turbulent combustion models of the PaSR class and plansfor the development of these models in relation to the combustion chambers of gas turbine units]. *Goren. Vzryv (Mosk.) — Combustion and Explosion* 15(4):48–57.
13. Ferrarotti, M., Z. Li, and A. Parente. 2019. On the role of mixing models in the simulation of MILD combustion using finite-rate chemistry combustion models. *P. Combust. Inst.* 37(4):4531–4538. doi: 10.1016/j.proci.2018.07.043.
14. Menter, F. R. 1994. Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA J.* 32(8):1598–1605.
15. Menter, F. R., M. Kuntz, and R. Langtry. 2003. Ten years of industrial experience with the SST turbulence model. *Turbulence Heat Mass Transfer* 4(1):625–632.
16. Sabelnikov, V., and C. Fureby. 2013. LES combustion modeling for high Re flames using a multi-phase analogy. *Combust. Flame* 160(1):83–96. doi: 10.1016/j.combustflame.2012.09.008.
17. Basevich, V., A. Belyaev, and S. Frolov. 1998. "Global" kinetic mechanisms for calculating turbulent reactive flows. I. The basic chemical heat release process. *Chem. Phys. Rep.* 17(9):1747–1772.
18. Libby, P. A., and K. N. C. Bray. 1981. Countergradient diffusion in premixed turbulent flames. *AIAA J.* 19(2):205–213.
19. Zhang, S., and C. J. Rutland. 1995. Premixed flame effects on turbulence and pressure-related terms. *Combust. Flame* 102(4):447–461. doi: 10.1016/0010-2180(95)00036-6.
20. Sabelnikov, V. A., A. N. Lipatnikov., S. Nishiki, *et al.* 2021. Dissipation and dilatation rates in premixed turbulent flames. *Phys. Fluids* 33(3). doi: 10.1063/5.0039101.
21. Lindstedt, R. P., and E. M. Vaos. 1999. Modeling of premixed turbulent flames with second moment methods. *Combust. Flame* 116(4):461–485. doi: 10.1016/S0010-2180(98)00058-3.
22. Lebedev, A. B., K. Y. Yakubovskii, and P. D. Toktaliev. 2018. Numerical modeling of steady and unsteady combustion regimes of methane–air mixture in research combustion chamber with step. *J. Phys. Conf. Ser.* 1261(1):012020. doi: 10.1088/1742-6596/1261/1/012020.

Received July 24, 2024

Contributor

Balabanov Roman A. (b. 1999) — postgraduate student, Moscow Institute of Physics and Technology (MIPT), 9 Institutsky Lane, Dologoprudny 141701, Moscow Region, Russian Federation; engineer, Central Aerohydrodynamic Institute named after Prof. N. E. Zhukovky (TsAGI), 1 Zhukovsky Str., Zhukovsky 140180, Moscow Region, Russian Federation; balabanov.ra@phystech.edu